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Technical Memorandum 94-113

Transforming an Ultrasonic Digitizer into an Accurate Three-Dimensional Position Measurement System for Robotic Applications

by

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Approved By:

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Department of National Defence

Canada

ABSTRACT

The Nondestructive Evaluation Group of the Defence Research Establishment Pacific (DREP) has transformed a commercial ultrasonic digitizer into an accurate three-dimensional position measurement system to guide a surface scanning robot. Four ultrasonic receivers were configured to produce the three dimensional position of an ultrasonic transmitter. By using a second transmitter to measure the speed of sound, the accuracy of the commercial digitizer was improved by a factor of five.

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1. INTRODUCTION

Today, CF-18 aircraft are inspected for defects by manually scanning suspect areas using ultrasonic and electromagnetic techniques. This is time consuming and unreliable. The Defence Research Establishment Pacific (DREP) proposes that a scanning robot should save time and produce accurate repeatable results. Delaminations as small as 1 mm long must be monitored for growth every few months. Since the available manipulator, the PUMA 560, can't achieve this accuracy unaided, an accurate three-dimensional position measuring system is needed to improve the positioning accuracy of the manipulator.

Such a system must meet several specifications, the most important of which is that it is accurate to 1 mm. Since the PUMA manipulator works in Cartesian coordinates, control would be simpler if the measurement system also produced Cartesian coordinates. Because manipulators generally have a very limited payload capability, any sensor mounted on the end-effector would have to be small. In addition, the system operating range must be sufficient to encompass the manipulator's work envelope. Finally, since the measurement system is intended as a sensor for a control loop, calculation of a coordinate set should be sufficiently fast to maintain the accuracy requirement.

This report describes an approach which adapts a commercial ultrasonic digitizer. Although position accuracy is emphasized, other specifications are also examined.

Previous work with ultrasonic range sensors by Canali et al.[1] showed that range accuracy is vulnerable to temperature. By measuring and compensating for temperature, Canali showed a definite accuracy improvement. Smaller effects due to humidity and pressure were ignored. The approach described in this report compensates for all three environmental factors.

1.1.The ultrasonic digitizer

The ultrasonic digitizer is a commercial device consisting of eight multiplexed transmitters and four receivers. Figure 1 shows how it was used in conjunction with a manipulator. Each transmitter, a spark gap that emits a broad band ultrasound signal, has a mass of less than 20g and consequently, does not significantly affect the payload capacity of the manipulator. Each receiver is optimized to receive 50 kHz sound waves. Range is determined by multiplying the speed of sound by the time of travel, measured from when the spark is triggered to when the receiver detects a pulse.

2. THEORY

2.1.Measuring ranges

An ultrasonic digitizer determines distance by measuring the time it takes for a sound wave to pass from a transmitter to a receiver. Critical to its accuracy is an accurate measurement of the velocity of sound, given by Laplaces' formula,[2]

$$V = \sqrt{\frac{\gamma \cdot R_o \cdot T}{M}} \qquad (1)$$

where V = velocity of sound in dry air
T = Kelvin degrees (273.16 + degrees Celsius)
Ro = 8314 J/kg K - universal gas constant
γ = specific heat ratio
M = average molecular weight.

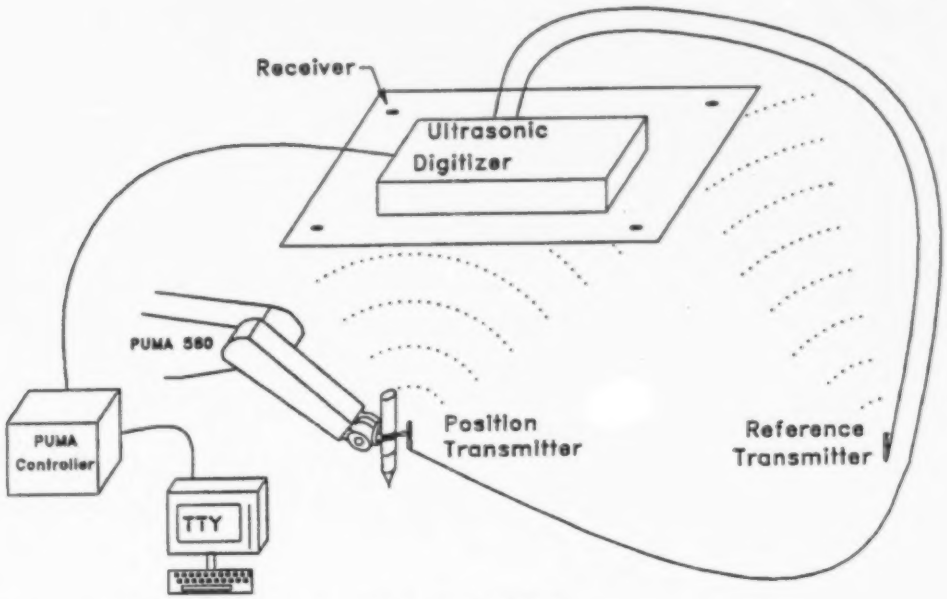

Figure 1: Configuration of the ultrasonic digitizer

For dry air,

γ = 1.4
M = 29.

Linearising around 0°C, Equation 1 becomes,[3]

$$V = 331.5 + 0.607t \qquad (2)$$

where t = temperature (°C).

Water vapor in the air causes both γ and M to decrease, resulting in the following correction,[4]

$$V_{wet} = \left(1 + 0.16\, H \frac{P_{sat}}{P_{air}} \right) V_{dry} \qquad (3)$$

where, H = humidity ratio

P_{sat} = partial pressure of H_2O at saturation (tabulated in Appendix A)

P_{air} = 760 mm of Hg at sea level.

The temperature effect is normally much greater than the humidity effect. A 10°C rise in temperature produces a 2% change, while a 100% rise in humidity produces a 0.3% change.

2.2.Coordinates from ranges

Receiver and transmitter geometry, shown in Figure 1, dictate how three ultrasonic ranges can be converted into a three-dimensional coordinate.

The derivation starts with a simple two dimensional model as shown in Figure 2.

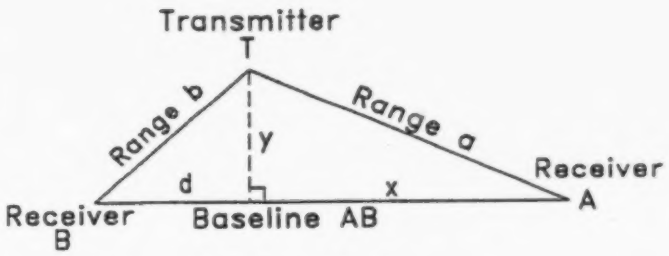

Figure 2: Two dimensional digitizer

The transmitter is at T and the receivers are at A and B. The measured ultrasonic ranges are represented by a and b. Using the Pythagorean theorem,

$$a^2 = x^2 + y^2 \qquad (4)$$

$$b^2 = d^2 + y^2 \qquad (5)$$

Equating y^2,

$$a^2 - x^2 = b^2 - d^2 \qquad (6)$$

$$d = (AB) - x \qquad (7)$$

Substituting d into equation 6 and solving for x yields,

$$x = \frac{a^2 - b^2 + (AB)^2}{2(AB)} \tag{8}$$

Solving for y from equation 4 yields,

$$y = \sqrt{a^2 - x^2} \tag{9}$$

The three dimensional case, shown in Figure 3, can be derived from the two dimensional case. T represents the transmitter, and points A, B and C represent the fixed receivers.

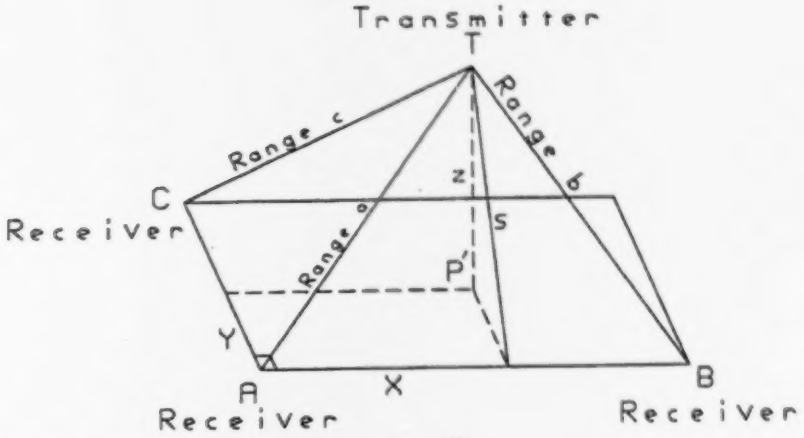

Figure 3: Three dimensional digitizer[5]

Viewing the pyramid from a normal to triangle ATB yields Figure 4.
From the two dimensional equation, equation 8, we can write,

$$x = \frac{a^2 - b^2 + (AB)^2}{2\,AB}. \tag{10}$$

Similarly for y,

$$y = \frac{a^2 - c^2 + (AC)^2}{2\,AC}. \tag{11}$$

Looking at Figure 3, knowing distances x, y and a and applying the Pythagorean theorem twice gives z,

$$z = \sqrt{a^2 - x^2 - y^2}. \tag{12}$$

The equations assume that angle CAB is a right angle.

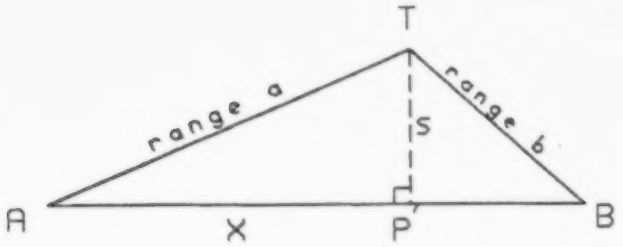

Figure 4: Normal view of triangle TAB

3. DIGITIZER LIMITATIONS

Although the digitizer's resolution is 0.1 mm, changes in the environment greatly degrade its accuracy.

Figure 5 shows the vulnerability of the digitizer's measurements to changes in air temperature. One curve shows the measurement fluctuations in relatively still air at a temperature of 20°C. The other curve shows the effect of a 14°C draft from an open outside door.

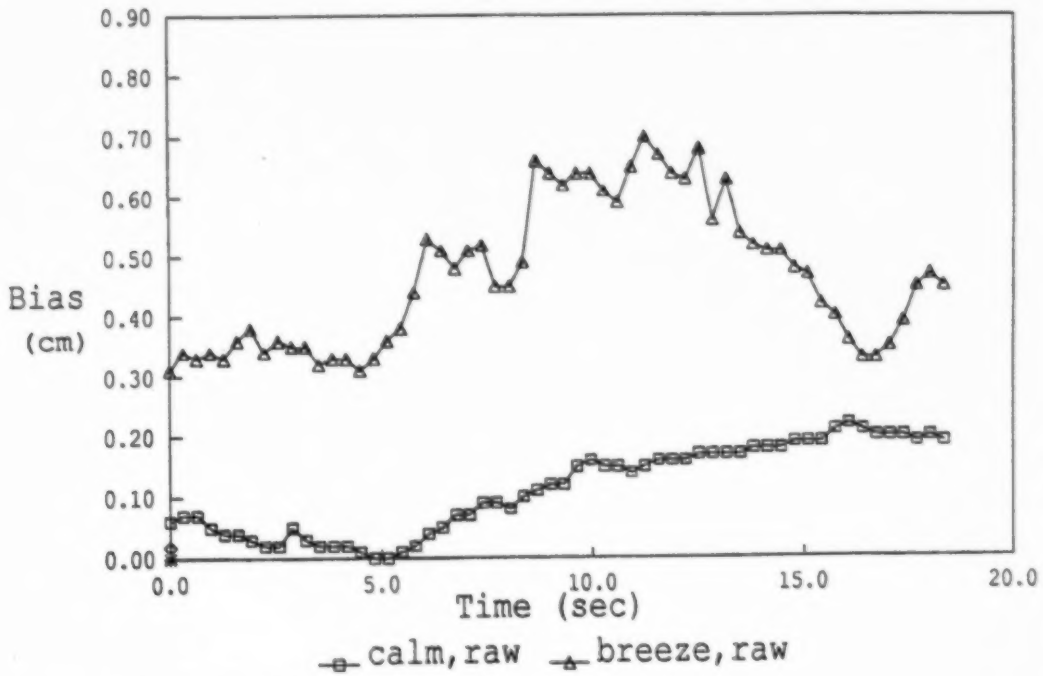

Figure 5: Digitizer bias at 161 cm range

Each receiver has two limitations: It has about a 180° field of view and its maximum reception range is 3.2m. Combined, these limitations constrain the work volume to a cube 1.8 m on the side.

4. IMPLEMENTATION

4.1.Improving accuracy

The errors seen in Figure 5 can be explained by temperature fluctuations. From the figure, the 14°C draft caused, on average, a 3.5 mm shift in the reading, which corresponds to a 0.2% shift in the speed of sound. To reduce these errors, a second reference transmitter was placed at a fixed known distance from a receiver to estimate the speed of sound for each measurement, as shown in Figure 1. It was positioned so that its path to the receiver is never blocked.

An important question is how frequently should these measurements be taken; Too frequently wastes computational time and too infrequently increases error. The worst fluctuation seen in Figure 5 is a 1.7 mm change during one measurement interval, about 0.32 seconds. Consequently, the speed of sound must be measured every 0.18 seconds to maintain an error less than 1 mm.

The resulting correction is,

$$d_{cor} = d_{ref} \frac{(M_{pos} - \delta)}{(M_{ref} - \delta)} \qquad (13)$$

where:

d_{cor} = corrected range from position transmitter (cm)

M_{ref} = range measurement from reference transmitter (cm)

Mpos = range measurement from position transmitter (cm)

d_{ref} = actual distance from reference transmitter (cm)

δ = 0.285 cm - delay in measurement electronics.

4.2.Converting range to coordinates

Equations 10,11,12 and 13 were implemented on the PUMA manipulator controller to convert ranges from three receivers to Cartesian coordinates. The data flow diagram in Appendix B describes how the algorithm was implemented. A 9600 baud serial RS232 line links the digitizer to the controller. The state diagram in Appendix C describes the communication.

5. RESULTS

5.1.Accuracy

Figures 6 and 7 show the improvement in accuracy for calm and breezy conditions respectively. The mean error was improved by a factor of 5.5.

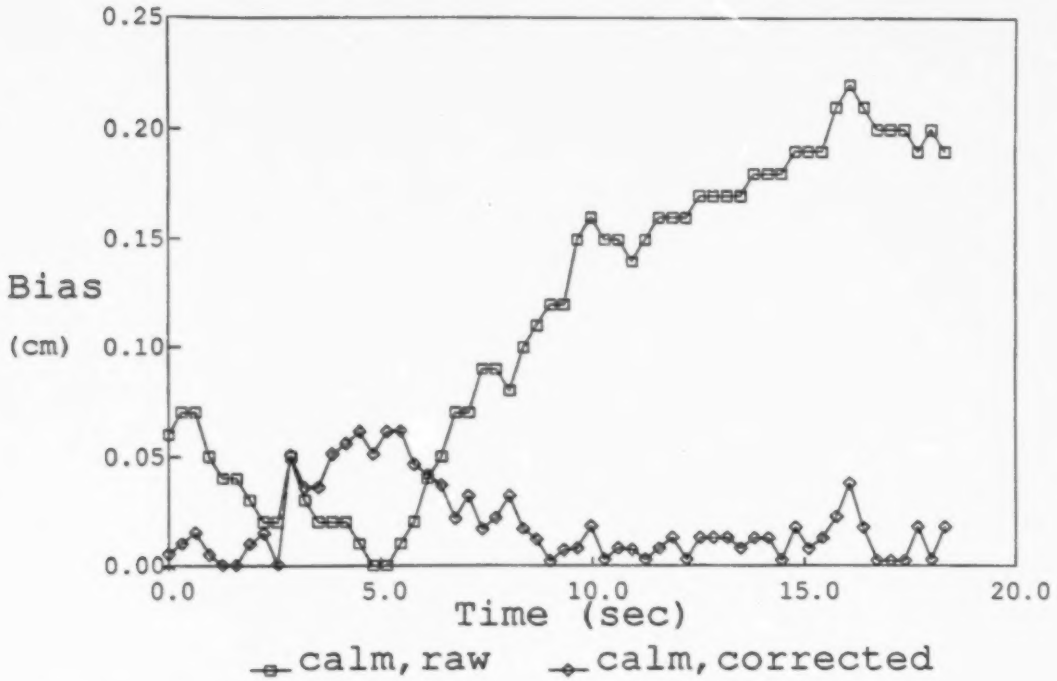

Figure 6: Range accuracy in calm air

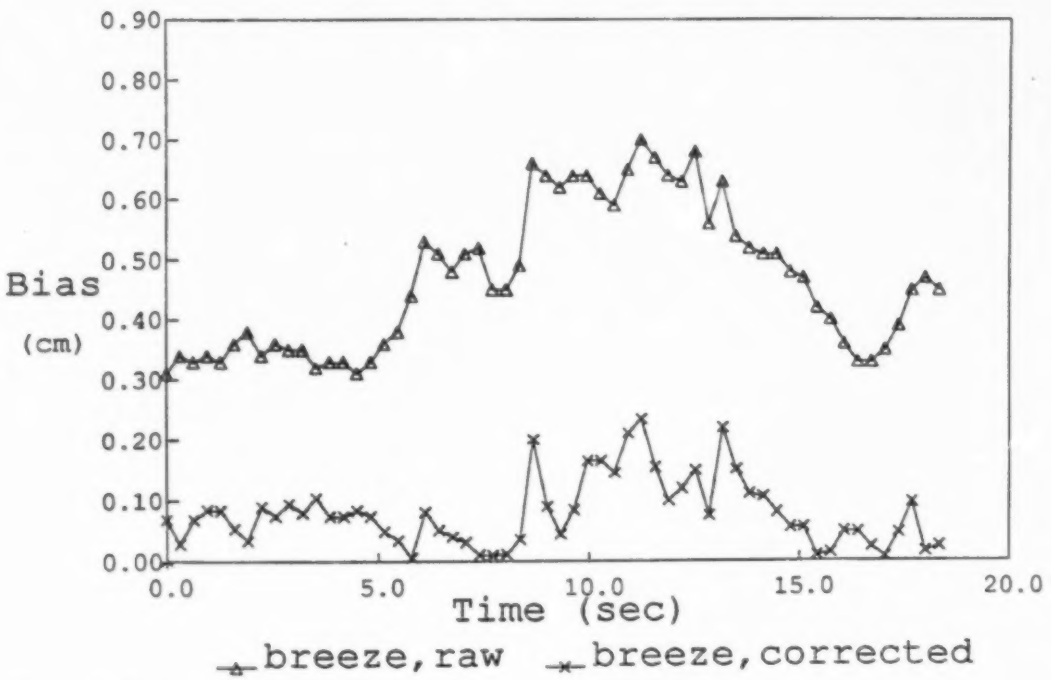

Figure 7: Range accuracy in breezy air

The results up to now were with the reference transmitter placed at a greater range than the position transmitter. Table I summarizes the degree of improvement when the reference is placed at different distances relative to the position transmitter. The results indicate that for best accuracy the reference transmitter should be placed at a range greater than the position transmitter.

Table I : Mean error for different reference distances

reference distance/ sensor distance		0.37	1.4	2.0
calm	raw(mm)	0.4	7.3	1.1
	corrected(mm)	0.1	1.9	0.2
	improvement factor	4	3.8	5.5
breezy	raw(mm)	6.6	9.1	4.7
	corrected(mm)	4.6	2.1	0.8
	improvement factor	1.4	4.3	5.9

sensor distance = 1.6m

5.2.Sampling rate

Another important criterion, besides accuracy, is the sampling rate. Figure 8 describes the timing of the communication link. The first line show when the measurements were requested and the second line shows when data were transmitted back. Besides showing a sampling rate of 7 samples/sec, it also indicates that the speed of sound is measured 35 msec after the measurement. This is well within the required 180 msec discussed in section 4.1.

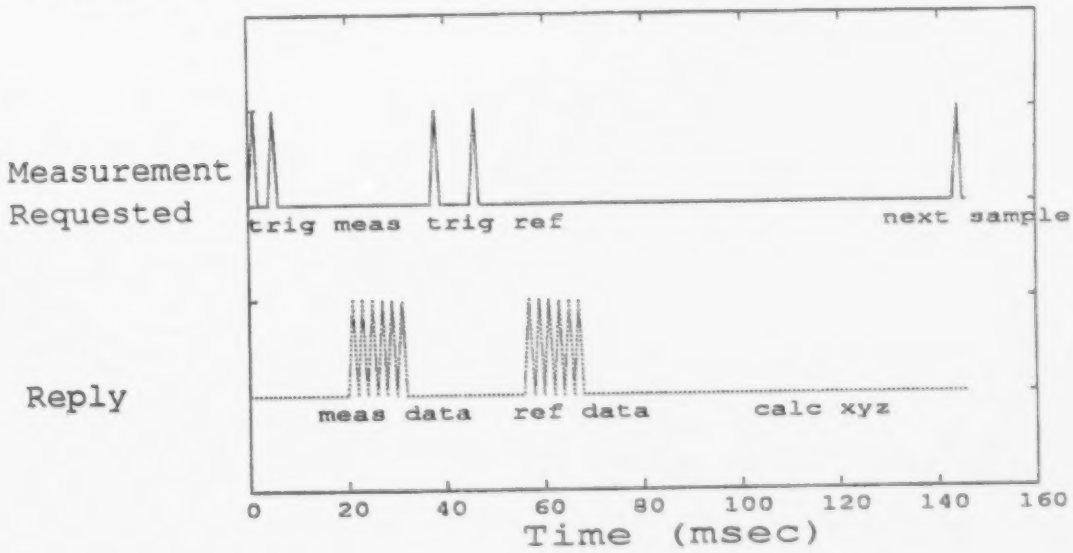

Figure 8: Timing diagram

5.3.Other error sources

The most difficult problem to overcome occurs when the transmitter-receiver path is blocked by the moving robotic arm. Errors can result from either sound passing through the interfering material, Figure 9, or when the signal takes a different (reflected) path, Figure 10. Figure 9 was generated by blocking the signal path with convenient materials of different density (a piece of paper, a hand, and a binder) in front of either the receiver or the position transmitter. Figure 10, showing multi-path error, was generated by slowly moving the transmitter past a flat metal object. During both tests, the range was kept relatively constant. Both sources of error are difficult to detect from the data alone, except that in both cases the reported range increased.

5.4.Improvements

There are two solutions to the blocked receiver problem.

The first solution uses all four receivers, instead of three, to calculate the best position. Data from a blocked receiver, detected by a sudden increase in range, would not be used. However, the receivers would have to be perfectly aligned to avoid a jump in the reported position.

A better solution would be to mount many transmitters on the end-effector. A program would analyze the manipulator-receiver geometry to dynamically select the unobstructed transmitter.

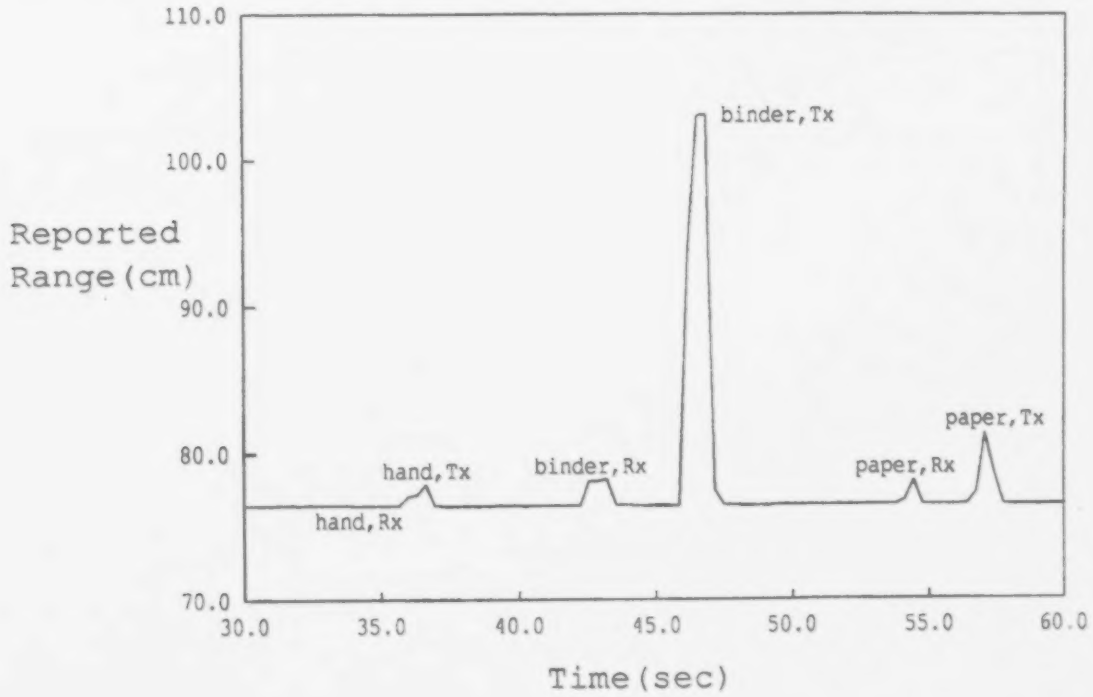

Figure 9: Error caused by blocked signal

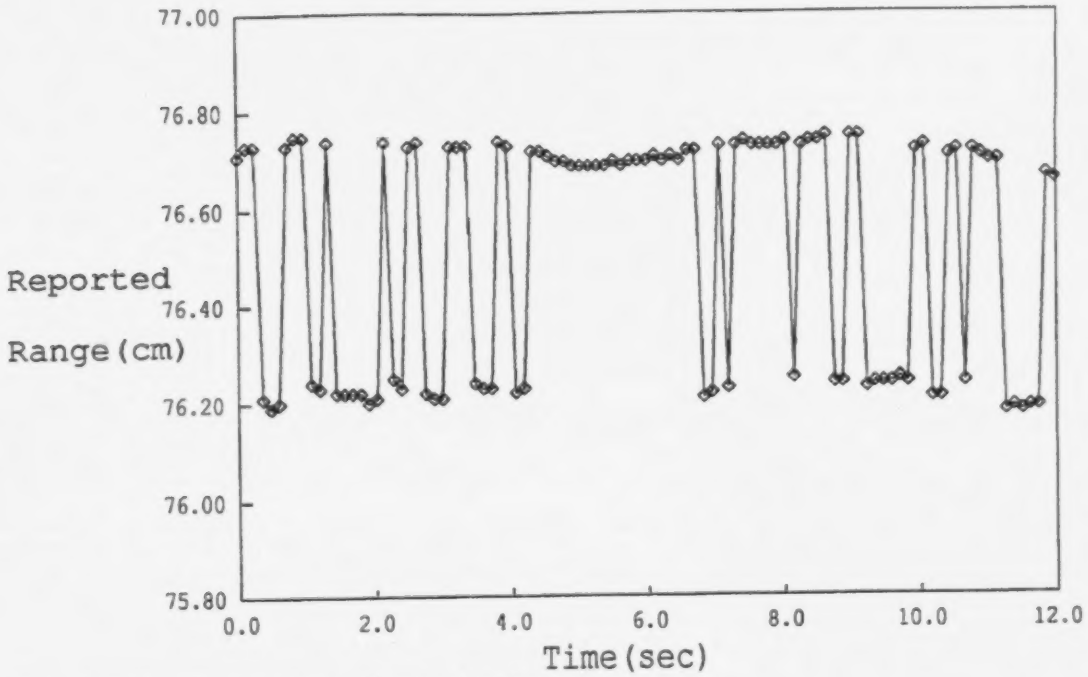

Figure 10: Error caused by different signal path

6. CONCLUSION

An ultrasonic position measurement system has been developed for a robotic surface scanner. The system developed used a commercial ultrasonic device. One transmitter was mounted on the end-effector and three receivers were mounted on three corners of a square board. The important criteria include accuracy, weight, work volume, Cartesian coordinate output, and sampling rate. The weight of the transmitter (less than 20g) is a very small fraction of the payload . The working volume of the system is a cube 1.8m on the side, enough for a PUMA 560 manipulator. The output is in Cartesian coordinates to simplify its use by the controller. When implemented on the PUMA 560 the calculation of a coordinate set took less than the 0.18 seconds required to maintain accuracy. A second transmitter, placed at a known distance from one of the receivers, was used to periodically measure the speed of sound to compensate for errors due to temperature, humidity, and pressure; the result, the requirement for 1mm accuracy was achieved -- a five-fold improvement.

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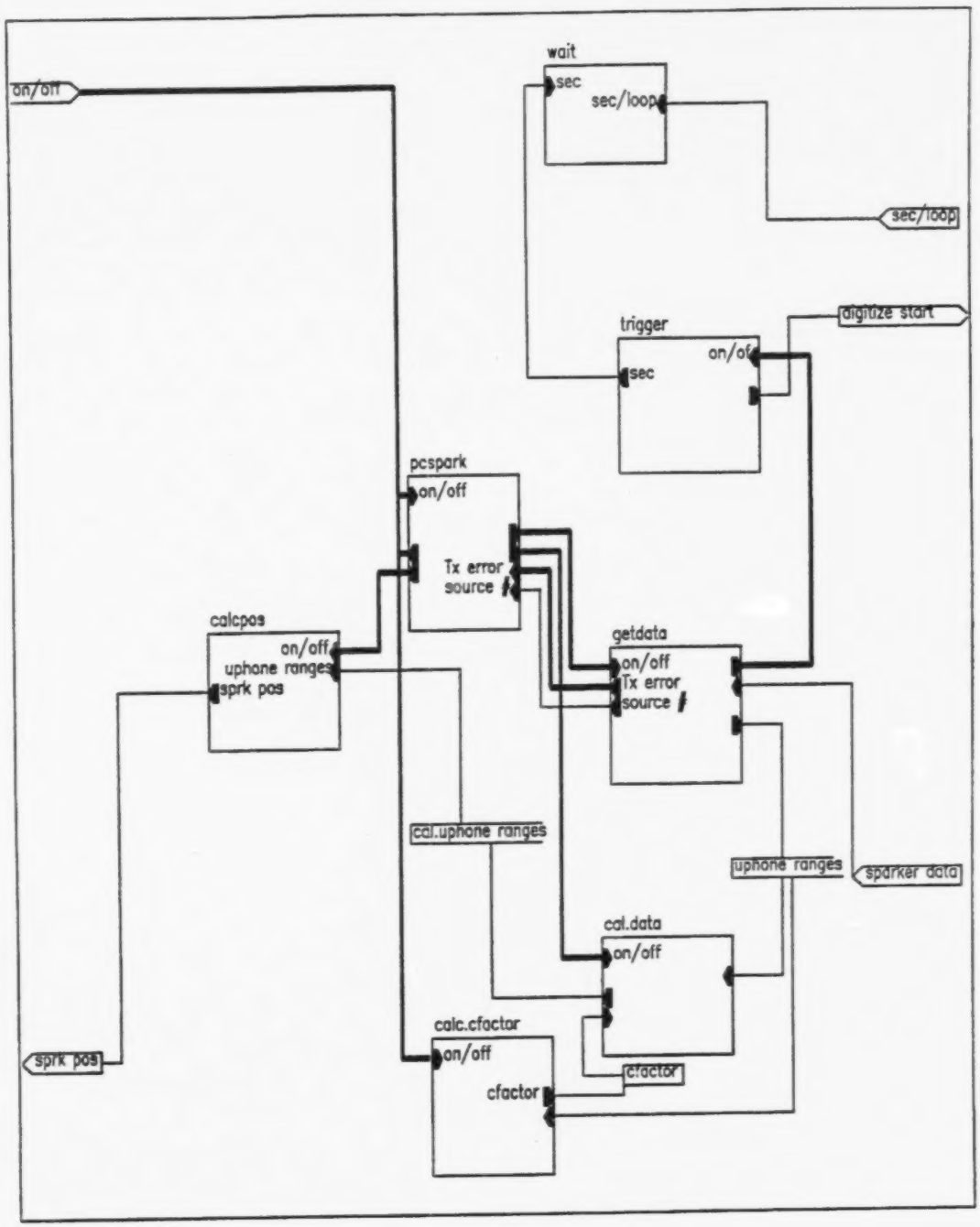
APPENDIX A: SATURATION PRESSURE AT VARIOUS TEMPERATURES[6]

Temperature (^oC)	Saturation pressure, P_{sat} (mm of Hg)
5	6.54
15	12.79
25	23.76
40	55.3

APPENDIX B: DATA FLOW DIAGRAM OF DIGITIZER SOFTWARE

The data flow diagram below summarize how the subroutines communicate. Thick lines represent either on/off control or event flags. Other lines represent discrete data packages. Boxes represent subroutines, and narrow three-sided boxes represent a data storage (files, global variables, stack, etc.). Pointed boxes represent an input or output to either hardware or other software modules.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sec/loop
on/off
sec/loop
digitize start
trigger
on/off
sec
pcspark
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Tx error
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on/off
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sprk pos
getdata
on/off
Tx error
source
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uphone ranges
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on/off
cfactor
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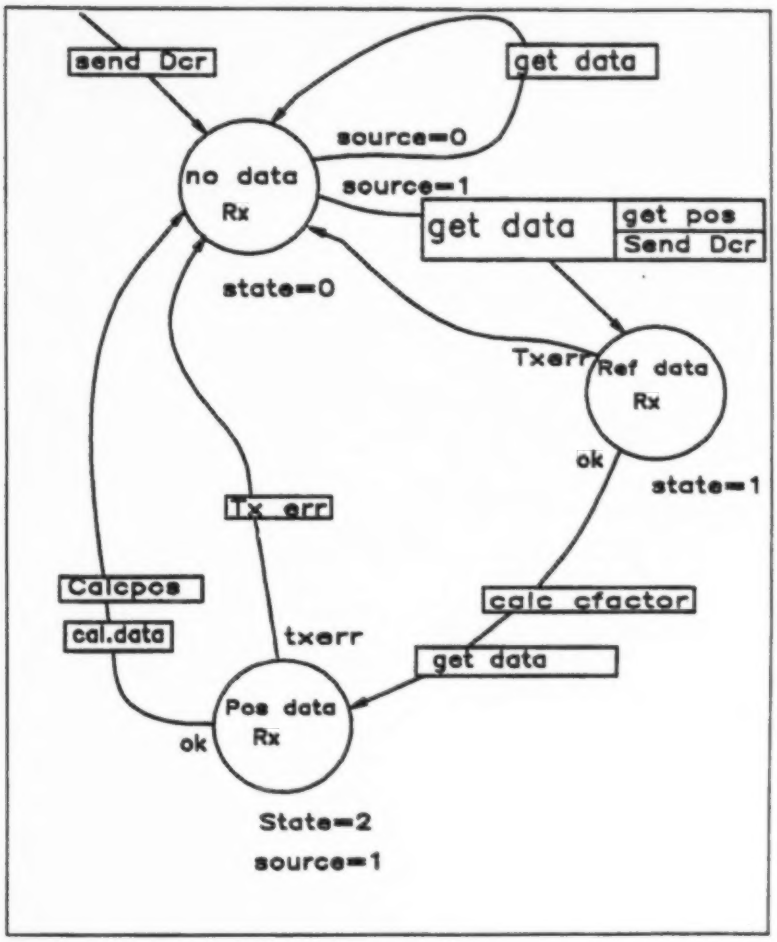
sprk pos

APPENDIX C: STATE DIAGRAM OF THE COMMUNICATION LINK



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sensor
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